Lecture 4: Storage Management

Administrivia

- Assignment 1 is due on September 7th @ 11:59pm

Layered Architecture

Overview

- We now understand what a database looks like at a **logical** level and how to write queries to read/write data from it (*i.e.*, **physical** level).
- We will next learn how to build software that manages a database.

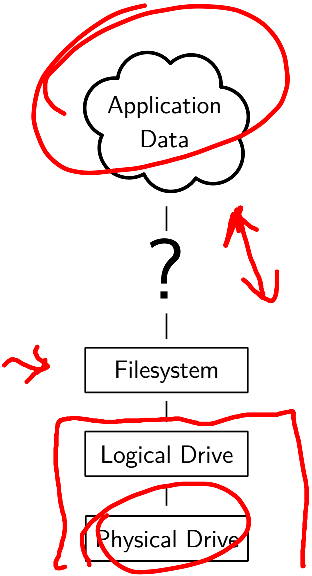
Anatomy of a Database System [Monologue]

- Process Manager
  - Manages client connections
- Query Processor
  - Parse, plan and execute queries on top of storage manager
- Transactional Storage Manager
  - Knits together buffer management, concurrency control, logging and recovery
- Shared Utilities
  - Manage hardware resources across threads

Anatomy of a Database System [Monologue] (2)

- Process Manager
  - Connection Manager + Admission Control
- Query Processor
  - Query Parser
  - Query Optimizer (*a.k.a.*, Query Planner)
  - Query Executor
- Transactional Storage Manager
  - Lock Manager
  - Access Methods (*a.k.a.*, Indexes)
  - Buffer Pool Manager
  - Log Manager
- Shared Utilities
  - Memory, Disk, and Networking Manager

The Problem


Application
Data
?
Filesystem
Logical Drive
Physical Drive

Requirements

There are different classes of requirements:

- Data Independence
  - application logic must be shielded from physical storage implementation details
  - physical storage can be reorganized
  - hardware can be changed
- Scalability
  - must scale to (nearly) arbitrary data size
  - efficiently access to individual tuples
  - efficiently update an arbitrary subset of tuples
- Reliability
  - data must never be lost
  - must cope with hardware and software failures
- ...

Layered Architecture

- implementing all these requirements on “bare metal” is hard
- and not desirable
- a DBMS must be maintainable and extensible

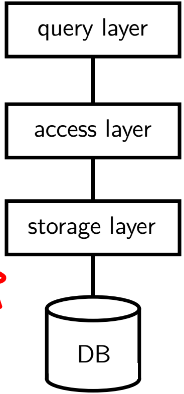
Instead: use a **layered architecture**

- the DBMS logic is split into levels of functionality
- each level is implemented by a specific layer
- each layer interacts only with the next lower layer
- simplifies and modularizes the code

A Simple Layered Architecture

Purpose

- query translation and optimization
- managing records and access paths
- DB buffer and hardware interface



Access Granularity

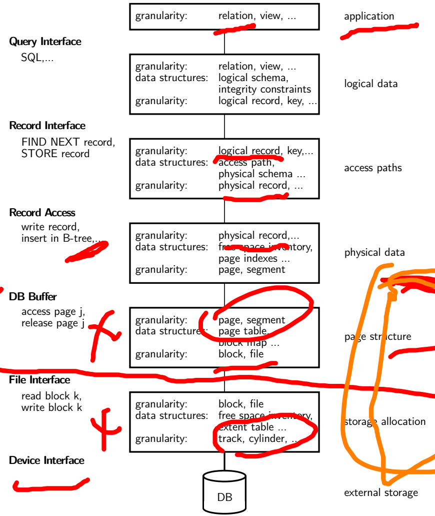
- declarative queries sets of records
- records
- page

A Simple Layered Architecture (2)

- layers can be characterized by the data items they manipulate
- lower layer offers functionality for the next higher level
- keeps the complexity of individual layers reasonable
- rough structure: physical $\rightarrow$ low level $\rightarrow$ high level

This is a reasonable architecture, but simplified.
A more detailed architecture is needed for a complete DBMS.

A More Detailed Architecture

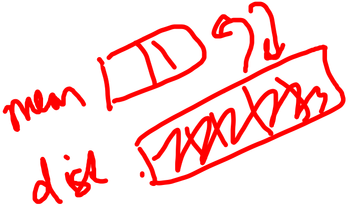


A More Detailed Architecture (2)

A few pieces are still missing:

- transaction isolation
- recovery

but otherwise it is a reasonable architecture.



Some system deviate slightly from this classical architecture

- many DBMSs nowadays delegate disk access to the OS
- some DBMSs delegate <u>**buffer management**</u> to the OS (tricky, though)
- a few DBMSs allow for direct logical record access
- ...

Hardware Properties

Impact of Hardware

Must take hardware properties into account when designing a storage system.

For a long time dominated by **Moore's Law**:

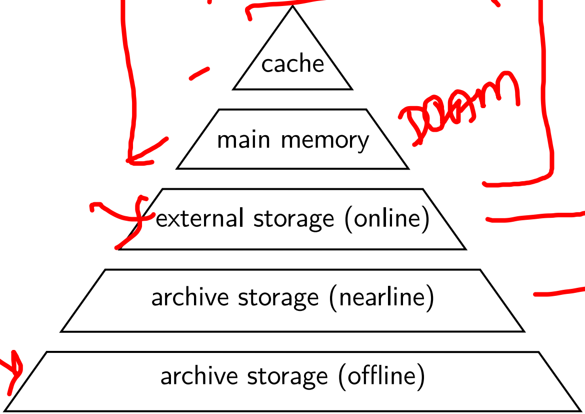
> *The number of transistors on a chip doubles every 18 month.*

Indirectly drove a number of other parameters:

- main memory size
- CPU speed
  - no longer true!
- HDD capacity
  - start getting problematic, too. density is very high
  - only capacity, not access time

Memory Hierarchy

capacity	latency
bytes	1ns
K-M bytes	<10ns
G bytes	<100ns
T bytes	ms
T bytes	sec
T-P bytes	sec-min

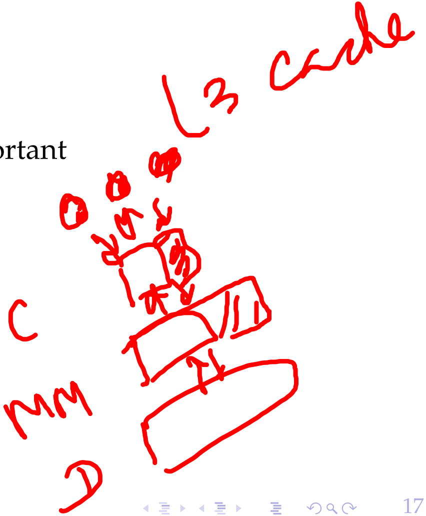


Memory Hierarchy (2)

There are huge gaps between hierarchy levels

- traditionally, main memory vs. disk is most important
- but memory vs. cache etc. also relevant

The DBMS must aim to maximize locality.



Hard Disk Access

Hard Disks are still the dominant external storage:

- rotating platters, mechanical effects
- transfer rate: ca. 150MB/s
- seek time ca. 3ms
- huge imbalance in random vs. sequential I/O!

Hard Disk Access (2)

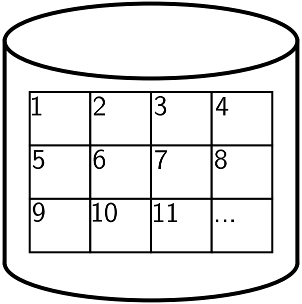
The DBMS must take these effects into account

- sequential access is much more efficient
- traditional DBMSs are designed to maximize sequential access
- gap is growing instead of shrinking
- even SSDs are slightly asymmetric (and have other problems)
- DBMSs try to reduce number of writes to random pages by organizing data in **contiguous blocks**.
- Allocating multiple pages at the same time is called a **segment**

Hard Disk Access (3)

Techniques to speed up disk access:

- do not move the head for every single tuple
- instead, load larger chunks. typical granularity: one **page**
- page size varies. traditionally 4KB, nowadays often 16K and more (**trade-off**)



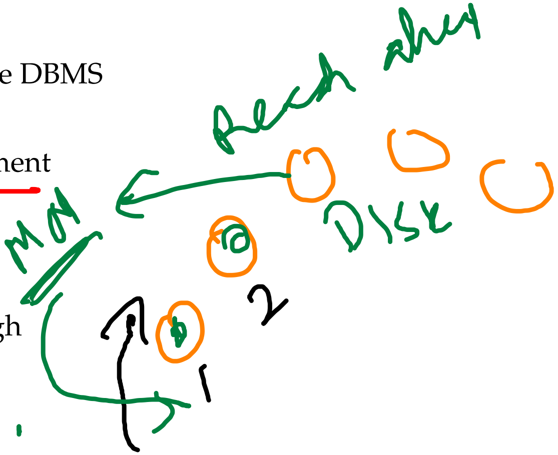
Hard Disk Access (4)

The page structure is very prominent within the DBMS

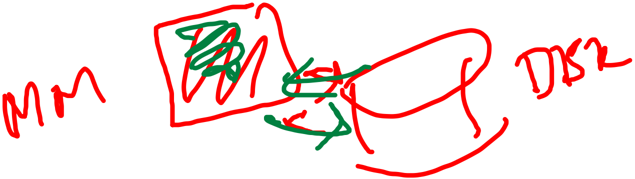
- granularity of I/O
- granularity of buffering/memory management
- granularity of recovery

Page is still too small to hide random I/O though

- sequential page access is important
- DBMSs use read-ahead techniques
- asynchronous write-back



Database System Architectures



Storage Management

Disk-Centric Database System

- The DBMS assumes that the primary storage location of the database is HDD.

Memory-Centric Database System (**MMDB**)

- The DBMS assumes that the primary storage location of the database is DRAM.

Buffer Management

The DBMS's components manage the movement of data between non-volatile and volatile storage.

Access Times

Access Time	Hardware	Scaled Time
0.5 ns	L1 Cache	0.5 sec
7 ns	L2 Cache	7 sec
100 ns	DRAM	100 sec
350 ns	NVM	6 min
150 us	SSD	1.7 days
10 ms	HDD	16.5 weeks
30 ms	Network Storage	11.4 months
1 s	Tape Archives	31.7 years

Source: Latency numbers every programmer should know

Disk-Oriented DBMS

Design Goals

- Allow the DBMS to manage databases that exceed the amount of memory available.
- Reading/writing to disk is expensive, so it must be managed carefully to avoid large stalls and performance degradation.

Disk-Oriented DBMS

Query execution engine ⟶ Storage Manager: Get Page 2

Memory | Buffer Pool

Page Directory	-	-	-

Disk | Database File

Page Directory	8	5	1	4	7	3	2	9	6

Disk-Oriented DBMS

- Each page has a **header** with the page's metadata (*e.g.*, page number, free space bitmap)
- Query execution engine gets pointer to page 2
  - Interprets the contents of page 2 using the header
- **Page directory** is typically implemented as a hash table
  - page number ⟶ buffer pool slot
  - page number ⟶ file block
- Page migration between disk and memory is known as buffer management

Why not use the OS?

- One can use **memory mapping (mmap)** to store the contents of a file into a process' address space.
- The OS is responsible for moving data for moving the files' pages in and out of memory.

Problems

- What if we allow multiple threads to access the mmap files to hide page fault stalls?
- This works good enough for read-only access.
- It is complicated when there are multiple writers.

Why not use the OS?

- There are some solutions to this problem:
  - **madvise:** Tell the OS how you expect to read certain pages.
  - **mlock:** Tell the OS that memory ranges cannot be paged out.
  - **msync:** Tell the OS to flush memory ranges out to disk.
- Database systems using mmap
  - Full Usage: MonetDB, LMDB, *e.t.c.*
  - Partial Usage: mongoDB, MemSQL, *e.t.c.*

Why not use the OS?

- DBMS (almost) always wants to control things itself and can do a better job at it.
  - Flushing dirty pages to disk in the correct order.
  - Specialized prefetching.
  - Buffer replacement policy.
  - Thread/process scheduling.

Storage Management

- File Storage
- Page Layout
- Tuple Layout

File Storage

File Storage

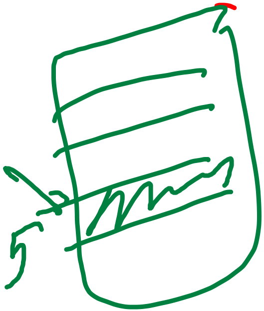
- The DBMS stores a database as one or more files on disk.
  - The OS doesn't know anything about the contents of these files.
- Early systems in the 1980s used custom filesystems on raw storage.
  - Some "enterprise" DBMSs still support this.
  - Most newer DBMSs do not roll their own filesystem

Storage Manager

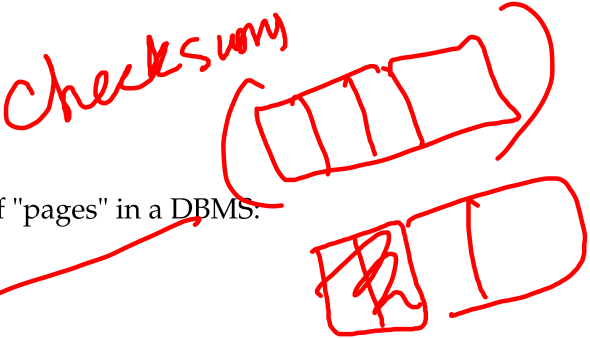
- The **storage manager** is responsible for maintaining a database's files.
  - Some do their own **scheduling** of I/O operations to improve spatial and temporal locality of pages.
- It organizes the files as a collection of pages.
  - Tracks data being read from and written to pages.
  - Tracks the available free space.

Database Pages

- A **page** is a fixed-size block of data.
  - It can contain tuples, meta-data, indexes, log records. . .
  - Most systems do not mix page types.
  - Some systems require a page to be self-contained. Why?
- Each page is given a unique identifier.
  - The DBMS uses an **indirection layer** to map page ids to physical locations.
  - This is implemented as a page directory table.



Database Pages



- There are three different notions of "pages" in a DBMS:
  - Hardware Page (usually 4 KB)
  - OS Page (usually 4 KB)
  - Database Page (512 B – 16 KB)
- By hardware page, we mean at what level the device can guarantee a "failsafe write".

Page Storage Architectures

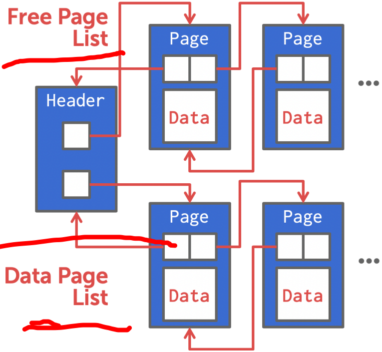
- Different DBMSs manage pages in files on disk in different ways.
  - **Heap File Organization**
  - Sequential / Sorted File Organization
  - Hashing File Organization
- At this point in the hierarchy we don't need to know anything about what is inside of the pages.

Database Heap

- A **heap file** is an unordered collection of pages where tuples are stored in random order.
  - Create / Get / Write / Delete Page
  - Must also support iterating over all pages.
- Need meta-data to keep track of what pages exist and which ones have free space.
- Two ways to represent a heap file:
  - Linked List
  - Page Directory

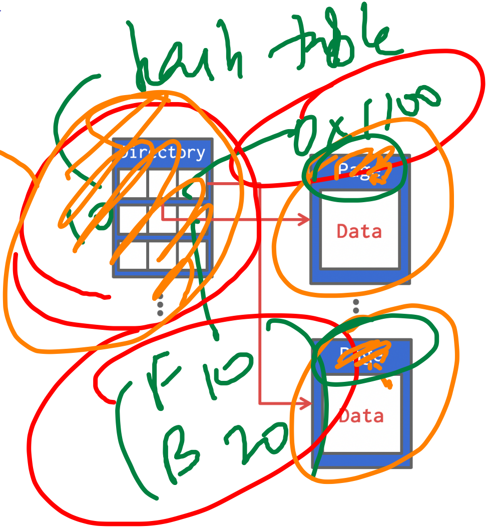
Heap File Organization: Linked List

- Maintain a **header page** at the beginning of the file that stores two pointers:
  - HEAD of the **free page list**.
  - HEAD of the **data page list**.
- Each page keeps track of the number of free slots in itself.



Heap File Organization: Page Directory

- The DBMS maintains special pages that tracks the location of data pages in the database files.
- The directory also records the number of free slots per page.
- The DBMS has to make sure that the directory pages are in sync with the data pages.



Page Layout

Page Header

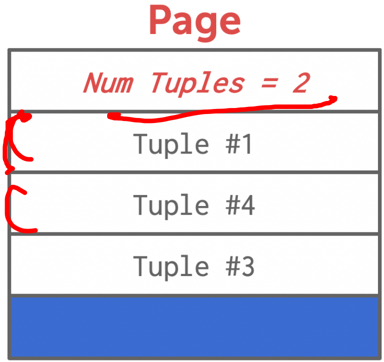
- Every page contains a header of meta-data about the page's contents.
  - Page Size
  - Checksum
  - DBMS Version
  - Transaction Visibility
  - Compression Information
- Some systems require pages to be **self-contained** (*e.g.*, Oracle).

Page Layout

- For any page storage architecture, we now need to understand how to organize the data stored inside of the page.
  - We are still assuming that we are only storing tuples.
- Two approaches:
  - Tuple-oriented
  - Log-structured

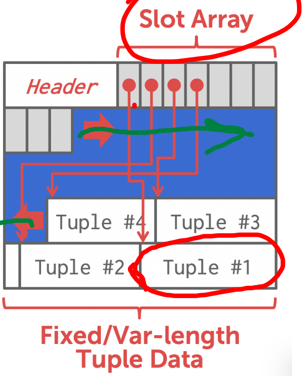
Tuple Storage

- How to store tuples in a page?
- Strawman Idea: Keep track of the number of tuples in a page and then just append a new tuple to the end.
  - What happens if we delete a tuple?
  - What happens if we have a variable-length attribute?



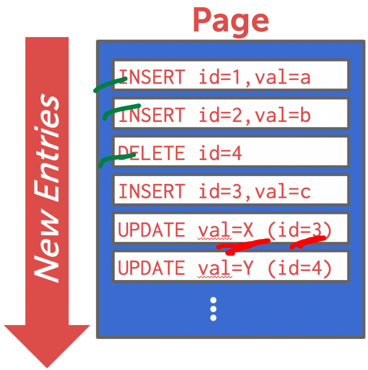
Slotted Pages

- The most common page layout scheme is called slotted pages.
- The **slot array** maps "slots" to the tuples' starting position offsets.
- The header keeps track of:
  - The number of used slots
  - The offset of the starting location of the last slot used.



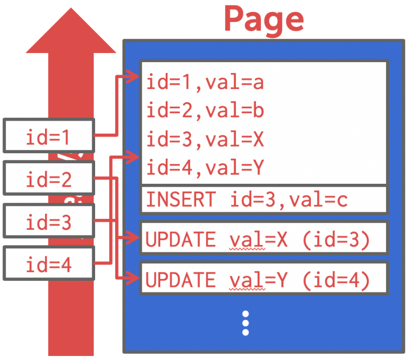
Log-structured File Organization

- Instead of storing tuples in pages, the DBMS only stores log records.
- The system appends log records to the file of how the database was modified:
  - Inserts store the entire tuple.
  - Deletes mark the tuple as deleted.
  - Updates contain the delta of just the attributes that were modified.



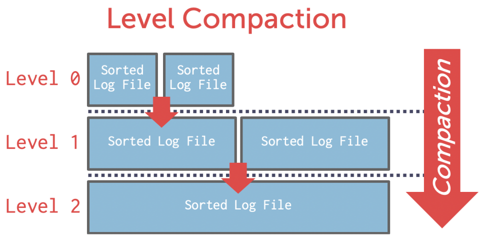
Log-structured File Organization

- To read a record, the DBMS scans the log backwards and "recreates" the tuple to find what it needs.
- Build indexes to allow it to jump to locations in the log.
- Periodically compact the log.



Log-structured Compaction

- Compaction coalesces larger log files into smaller files by removing unnecessary records.



Tuple Layout

Tuple Layout

- A tuple is essentially a sequence of bytes.
- It's the job of the DBMS to interpret those bytes into attribute types and values.

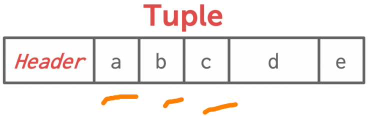
Tuple Header

- Each tuple is prefixed with a header that contains meta-data about it.
    - Visibility info (concurrency control)
    - Bit map for keeping track of `NULL` values.
- We do not need to store meta-data about the schema. Why?

Tuple Data

- Attributes are typically stored in the order that you specify them when you create the table.
- This is done for software engineering reasons.

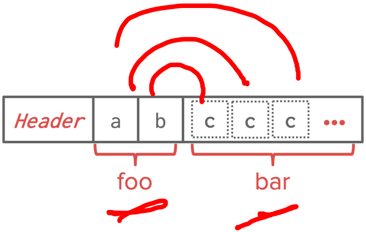
```
CREATE TABLE foo (
        a INT PRIMARY KEY,
        b INT NOT NULL,
        c INT,
        d DOUBLE,
        e FLOAT
);
```



Denormalized Tuple Data

- Can physically **denormalize** (e.g., "pre join") related tuples and store them together in the same page.
  - Potentially reduces the amount of I/O for common workload patterns.
  - Can make updates more expensive.
- Not a new idea.
  - IBM System R did this in the 1970s.
  - Several NoSQL DBMSs do this without calling it physical denormalization.

```
CREATE TABLE foo (
        a INT PRIMARY KEY,
        b INT NOT NULL
);
CREATE TABLE bar (
        c INT PRIMARY KEY,
        a INT REFERENCES foo (a)
);
```



Tuple IDs

- The DBMS needs a way to keep track of individual tuples.
- Each tuple is assigned a unique record identifier.
  - Most common: page_id + offset/slot
  - Can also contain file location info.
- An application **cannot** rely on these ids to mean anything.
- Examples
  - PostgreSQL: CTID (6-bytes)
  - SQLite: ROWID (10-bytes)
  - Oracle: ROWID (8-bytes)

Conclusion

- Database systems have a layered architecture.
- Design of database system components affected by hardware properties.
- Database is physically organized as a collection of pages on disk.
- Different ways to manage pages and tuples.

Next Class

- Value Representation
- Storage Models

References I